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Appendix A

IBOC FM Transmission Specification

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1 Scope

The iBiquity Digital Corporation's iDAB™ system is designed to permit a smooth evolution from current analog Amplitude Modulation (AM) and Frequency Modulation (FM) radio to a fully digital in-band on-channel (IBOC) system. This system delivers digital audio and data services to mobile, portable, and fixed receivers from terrestrial transmitters in the existing Medium Frequency (MF) and Very High Frequency (VHF) radio bands. Broadcasters may continue to transmit analog AM and FM simultaneously with the new, higher-quality and more robust digital signals, allowing themselves and their listeners to convert from analog to digital radio while maintaining their current frequency allocations.

2 Abbreviations, Symbols, and Conventions

2.1 Introduction

Section 2 presents the following items pertinent to a better understanding of this document:

- Abbreviations and Acronyms
- Presentation Conventions
- Mathematical Symbols
- FM System Parameters

Note: A glossary defining the technical terms used herein is provided at the end of this document.

2.2 Abbreviations and Acronyms

AM	Amplitude Modulation
BC	L1 Block Count
BPSK	Binary Phase Shift Keying
DD	Analog Diversity Delay Control
DDI	Analog Diversity Delay Indicator
EAS	Emergency Alert System
FCC	Federal Communications Commission
FM	Frequency Modulation
GPS	Global Positioning System
IBOC	In-Band On-Channel
IDS	IBOC Data Service
IP	Interleaving Process
kbit/sec	kilobits per second
L1	Layer 1
L2	Layer 2
MF	Medium Frequency
MP1–MP7	Primary Service Modes 1 through 7
MS1–MS4	Secondary Service Modes 1 through 4
N/A	Not Applicable
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
P1–P3	Primary Logical Channels 1 through 3
PIDS	Primary IBOC Data Service Logical Channel
PM	Primary Main
PSM	Primary Service Mode
PX	Primary Extended
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RSID	Reference Subcarrier Identification
S1–S5	Secondary Logical Channels 1 through 5
SAP	Service Access Point
SB	Secondary Broadband

SCA	Subsidiary Communications Authorization
SCCH	System Control Channel
SCI	Secondary Channel Indicator
SCU	Service Control Unit
SDU	Service Data Unit
SIDS	Secondary IBOC Data Service Logical Channel
SM	Secondary Main
SP	Secondary Protected
SSM	Secondary Service Mode
SX	Secondary Extended
UTC	Universal Time Coordinated
VHF	Very High Frequency

2.3 Presentation Conventions

Unless otherwise noted, the following conventions apply to this document:

- In this document, all provisions enclosed in braces{ } will either be provided in the future or are anticipated to be subject to change upon review.
- All items in the glossary are presented in italics upon their first usage in the text.
- All vectors are indexed starting with 0.
- The element of a vector with the lowest index is considered to be first.
- In drawings and tables, the leftmost bit is considered to occur first.
- Bit 0 of a byte or word is considered the least significant bit.
- When presenting the dimensions of a matrix, the number of rows is given first (e.g., an $n \times m$ matrix has n rows and m columns).
- In timing diagrams, earliest time is on the left.

2.4 Mathematical Symbols

2.4.1 Variable Naming Conventions

The variable naming conventions defined below are used throughout this document.

Category	Definition	Examples
Lower and upper case letters	Indicates scalar quantities	i, j, J, g_{11}
Underlined lower and upper case letters	Indicates vectors	$\underline{u}, \underline{v}$
Double underlined lower and upper case letters	Indicates two-dimensional matrices	$\underline{\underline{u}}, \underline{\underline{v}}$
$[i]$	Indicates the i^{th} element of a vector, where i is a non-negative integer	$\underline{u}[0], \underline{v}[1]$
$[]$	Indicates the contents of a vector	$\underline{v} = [0, 10, 6, 4]$
$[i][j]$	Indicates the element of a two-dimensional matrix in the i^{th} row and j^{th} column, where i and j are non-negative integers	$\underline{\underline{u}}[i][j], \underline{\underline{v}}[i][j]$

Category	Definition	Examples
$\begin{bmatrix} \end{bmatrix}$	Indicates the contents of a matrix	$\underline{\underline{m}} = \begin{bmatrix} 0 & 3 & 1 \\ 2 & 7 & 5 \end{bmatrix}$
$n \dots m$	Indicates all the integers from n to m , inclusive	$3 \dots 6 = 3, 4, 5, 6$
$n:m$	Indicates bit positions n through m of a binary sequence or vector	Given a binary vector $i = [0, 1, 1, 0, 1, 1, 0, 0]$, $i_{2:5} = [1, 0, 1, 1]$

2.4.2 Arithmetic Operators

The arithmetic operators defined below are used throughout this document.

Category	Definition	Examples
\cdot	Indicates a multiplication operation	$3 \cdot 4 = 12$
$\text{INT}()$	Indicates the integer portion of a real number	$\text{INT}(5/3) = 1$ $\text{INT}(-1.8) = -1$
$a \text{ MOD } b$	Indicates a modulo operation	$33 \text{ MOD } 16 = 1$
\oplus	Indicates modulo-2 binary addition	$1 \oplus 1 = 0$
$ $	Indicates the concatenation of two vectors	$\underline{B} = [\underline{S} \mid \underline{E}]$ The resulting vector \underline{B} consists of the elements of \underline{S} followed by the elements of \underline{E} .
j	Indicates the square-root of -1	$j = \sqrt{-1}$
$\text{Re}()$	Indicates the real component of a complex quantity	If $x = (3 + j4)$, $\text{Re}(x) = 3$
$\text{Im}()$	Indicates the imaginary component of a complex quantity	If $x = (3 + j4)$, $\text{Im}(x) = 4$
Log_{10}	Indicates the base-10 logarithm	$\log_{10}(100) = 2$

2.5 FM System Parameters

The FM system parameters defined below are used throughout this document.

Parameter Name	Symbol	Units	Exact Value	Computed Value (to 4 significant figures)
OFDM Subcarrier Spacing	Δf	Hz	1488375/4096	363.4
Cyclic Prefix Width	α	none	7/128	5.469×10^{-2}
OFDM Symbol Duration	T_s	Sec.	$(1+\alpha) / \Delta f = (135/128) \cdot (4096/1488375)$	2.902×10^{-3}
OFDM Symbol Rate	R_s	Hz	$= 1/T_s$	344.5
L1 Frame Duration	T_f	Sec.	$65536/44100 = 512 \cdot T_s$	1.486
L1 Frame Rate	R_f	Hz	$= 1/T_f$	6.729×10^{-1}
L1 Block Duration	T_b	Sec.	$= 32 \cdot T_s$	9.288×10^{-2}
L1 Block Rate	R_b	Hz	$= 1/T_b$	10.77
L1 Block Pair Duration	T_p	Sec.	$= 64 \cdot T_s$	1.858×10^{-1}
L1 Block Pair Rate	R_p	Hz	$= 1/T_p$	5.383
Diversity Delay Frames	N_{dd}	none	3 = number of L1 frames of diversity delay	3

3 IBOC Layers

The IBOC detailed performance specifications are organized in terms of the International Standards Organization Open Systems Interconnection (ISO OSI) layered model. The definitions of this model are summarized below for reference:

- **Layer 1: Physical layer**
 - Modem, Interleaving, FEC, Scrambling
- **Layer 2: Data link layer**
 - Routing Layer 1 Frames to/from Layer 4 -- Minimal frame integrity checking.
- **Layer 3: Network layer -- Not used in IBOC**
- **Layer 4: Transport layer -- Builds services, reliable data delivery in format required for specific applications**
 - Digital Audio
 - Control Data and Text
 - File & Packet Delivery
- **Layer 5: Session layer -- Not used in IBOC**
- **Layer 6: Presentation layer -- Provides services like Encoding/Decoding**
 - Images
 - Text
 - Audio, PAC
- **Layer 7 Application layer 7: -- Provides means of exchanging information to the user via human machine interface**
 - Audio – blending, audio processing etc..
 - Text – Processing for display.
 - Video - Video image presentation.
 - Specialized applications like java applets etc..

Each OSI layer of the broadcasting system has a corresponding layer, termed a peer, in the receiving system. The functionality of these layers is such that the combined result of lower layers is to effect a virtual communication between a given layer and its peer on the other side.

For the purposes of this document covering the IBOC Transmission System only Layer 1 will be described.

3.1 FM Hybrid Layer 1

3.1.1 Introduction

Layer 1 of the FM system converts information and system control from Layer 2 (L2) into the FM IBOC waveform for transmission in the VHF band. The information and control is transported in discrete transfer frames via multiple logical channels through the Layer 1 service access points (SAPs). These transfer frames are also referred to as Layer 2 service data units (SDUs) and service control units (SCUs), respectively.

The L2 SDUs vary in size and format depending on the service mode. The service mode, a major component of system control, determines the transmission characteristics of each logical channel. After assessing the requirements of their candidate applications, higher protocol layers select service modes that most suitably configure the logical channels. The plurality of logical channels reflects the inherent flexibility of the system, which supports simultaneous delivery of various classes of digital audio and data.

Layer 1 also receives system control as SCUs from Layer 2. System control is processed in the System Control Processor.

This section presents the following:

- An overview of the waveforms and spectra
- An overview of the system control, including the available service modes

- An overview of the logical channels
- A high-level discussion of each of the functional components comprising the Layer 1 FM air interface

Note: Throughout this document, various system parameters are globally represented as mathematical symbols. Refer to Subsection 2.5 for their values.

3.2 Waveforms and Spectra

The design provides a flexible means of transitioning to a digital broadcast system by providing three new waveform types: Hybrid, Extended Hybrid, and All Digital. The Hybrid and Extended Hybrid types retain the analog FM signal, while the All Digital type does not. All three waveforms operate well below allocated *spectral emissions mask* as currently defined by the FCC.

The *digital signal* is modulated using *orthogonal frequency division multiplexing* (OFDM). OFDM is a parallel modulation scheme in which the data stream modulates a large number of orthogonal subcarriers, which are transmitted simultaneously. OFDM is inherently flexible, readily allowing the mapping of logical channels to different groups of subcarriers.

Refer to Section 5 for a detailed description of the spectra of the three-waveform types.

3.2.1 Hybrid Waveform

The digital signal is transmitted in *Primary Main (PM) sidebands* on either side of the analog FM signal in the *Hybrid waveform*. The power level of each sideband is approximately 23 dB below the total power in the analog FM signal. The *analog signal* may be monophonic or stereo, and may include subsidiary communications authorization (SCA) channels.

3.2.2 Extended Hybrid Waveform

In the *Extended Hybrid waveform*, the bandwidth of the Hybrid sidebands can be extended toward the analog FM signal to increase digital capacity. This additional spectrum, allocated to the inner edge of each Primary Main sideband, is termed the *Primary Extended (PX) sideband*.

3.2.3 All Digital Waveform

The greatest system enhancements are realized with the *All Digital waveform*, in which the analog signal is removed and the bandwidth of the primary digital sidebands is fully extended as in the Extended Hybrid waveform. In addition, this waveform allows lower-power digital *secondary sidebands* to be transmitted in the spectrum vacated by the analog FM signal.

3.3 System Control Channel

The *System Control Channel* (SCCH) transports control and status information. Primary and secondary service modes and *diversity delay* control are sent from Layer 2 to Layer 1, while synchronization information is sent from Layer 1 to Layer 2.

The service modes dictate all permissible configurations of the logical channels. There are a total of eleven service modes.

- The seven primary service modes are MP1, MP2, MP3, MP4, MP5, MP6, and MP7. They configure the primary logical channels.
- The four secondary service modes are MS1, MS2, MS3, and MS4. They configure the secondary logical channels.

3.4 Logical Channels

A logical channel is a signal path that conducts L2 SDUs in transfer frames into Layer 1 with a specific grade of service, determined by service mode. Layer 1 of the FM air interface provides ten logical channels to higher layer protocols. Not all logical channels are used in every service mode. Refer to subsection 3.4.1 through Subsection 3.4.3 for details.

3.4.1 Primary Logical Channels

There are four primary logical channels which are used with both the Hybrid and All Digital waveforms. They are denoted as P1, P2, P3, and PIDS. Table 3-1 shows the approximate information rate supported by each primary logical channel as a function of primary service mode.

Table 3-1 Approximate Information Rate of Primary Logical Channels

Service Mode	Approximate Information Rate (kbps)				Waveform
	P1	P2	P3	PIDS	
MP1	25	74	0	1	Hybrid
MP2	25	74	12	1	Extended Hybrid
MP3	25	74	25	1	Extended Hybrid
MP4	25	74	50	1	Extended Hybrid
MP5	25	74	25	1	Extended Hybrid, All Digital (With Analog)
MP6	50	49	0	1	Extended Hybrid, All Digital (With Analog)
MP7	25	98	25	1	Extended Hybrid, All Digital (With Analog)

3.4.2 Secondary Logical Channels

There are six secondary logical channels that are used only with the All Digital waveform. They are denoted as S1, S2, S3, S4, S5, and SIDS. Table 3-2 shows the approximate information rate supported by each secondary logical channel as a function of secondary service mode.

Table 3-2 Approximate Information Rate of Secondary Logical Channels

Service Mode	Approximate Information Rate (kbps)						Waveform
	S1	S2	S3	S4	S5	SIDS	
MS1	0	0	0	98	6	1	All Digital
MS2	25	74	25	0	6	1	All Digital
MS3	50	49	0	0	6	1	All Digital
MS4	25	98	25	0	6	1	All Digital

3.4.3 Logical Channel Functionality

Logical channels P1 through P3 are designed to convey audio and data. S1 through S5 can be configured to carry data or surround sound audio. Primary IBOC Data Service (PIDS) and Secondary IBOC Data Service (SIDS) logical channels are designed to carry IBOC Data Service (IDS) information.

The performance of each logical channel is completely described through three characterization parameters: *transfer*, *latency*, and *robustness*. Channel encoding, spectral mapping, interleaver depth, and diversity delay are the components of these characterization parameters. The service mode uniquely configures these components for each active logical channel, thereby allowing the assignment of appropriate characterization parameters.

In addition, the service mode specifies the framing and synchronization of the transfer frames through each active logical channel.

3.5 Functional Components

This subsection includes a high-level description of each Layer 1 functional block and the associated signal flow. Figure 3-1 is a functional block diagram of Layer 1 processing. Audio and data are passed from the higher OSI layers to the physical layer, the modem, through the Layer 1 Service Access points.

The flow of the signal is detailed in sections 3.5.1 through 3.5.8.

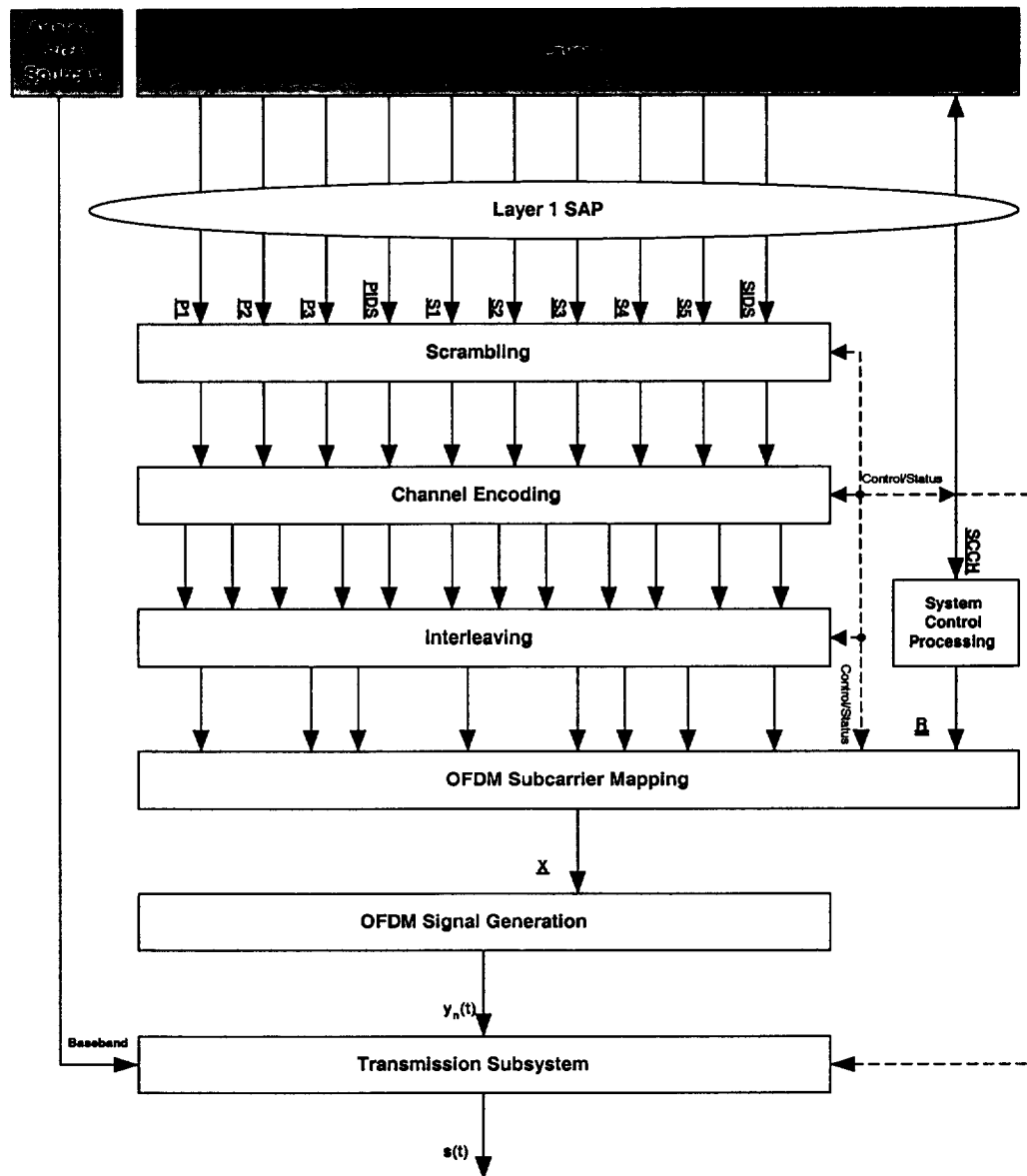


Figure 3-1 FM Air Interface Layer 1 Functional Block Diagram

3.5.1 Service Access Points

The L1 SAPs define the interface between Layer 2 and Layer 1 of the *system protocol stack*. Each logical channel and the SCCH have their own SAP. Each channel enters Layer 1 in discrete transfer frames, with unique size and rate determined by the service mode. These Layer 2 transfer frames are typically referred to as L2 SDUs and SCUs.

3.5.2 Scrambling

This function randomizes the digital data in each logical channel to “whiten” and mitigate signal periodicities when the waveform is demodulated in a conventional analog FM demodulator.

3.5.3 Channel Encoding

This function uses convolution encoding to add redundancy to the digital data in each logical channel to improve its reliability in the presence of channel impairments. The size of the logical channel vectors is increased in inverse proportion to the *code rate*. The encoding techniques are configurable by service mode. Diversity delay is also imposed on selected logical channels. At the output of the channel encoder, the logical channel vectors retain their identity.

3.5.4 Interleaving

Interleaving in time and frequency is employed to mitigate the effects of burst errors. The interleaving techniques are tailored to the VHF *fading* environment and are configurable by service mode. In this process, the logical channels lose their identity. The interleaver output is structured in a matrix format; each matrix is comprised of one or more logical channels and is associated with a particular portion of the transmitted spectrum.

3.5.5 System Control Processing

This function generates a matrix of *system control data sequences* which includes control and status (such as service mode), for broadcast on the reference subcarriers.

3.5.6 OFDM Subcarrier Mapping

This function assigns the interleaved matrices and the system control matrix to the *OFDM subcarriers*. One row of each active interleaver matrix is processed every *OFDM symbol* T_s to produce one output vector \underline{X} , which is a frequency-domain representation of the signal. The mapping is specifically tailored to the non-uniform interference environment and is a function of the service mode.

3.5.7 OFDM Signal Generation

This function generates the digital portion of the time-domain FM IBOC waveform. The input vectors are transformed into a shaped time-domain baseband pulse, $y_n(t)$, defining one OFDM symbol.

3.5.8 Transmission Subsystem

This function formats the baseband waveform for transmission through the VHF channel. Major sub-functions include symbol concatenation and frequency up-conversion. In addition, when transmitting the Hybrid waveform, this function modulates the analog source and combines it with the digital signal to form a composite Hybrid signal, $s(t)$, ready for transmission.

4 Functional Description

4.1 Introduction

OFDM Signal Generation receives complex, frequency-domain OFDM symbols from OFDM Subcarrier Mapping, and outputs time-domain pulses representing the digital portion of the FM IBOC signal. A conceptual block diagram of OFDM Signal Generation is shown in Figure 4-1.

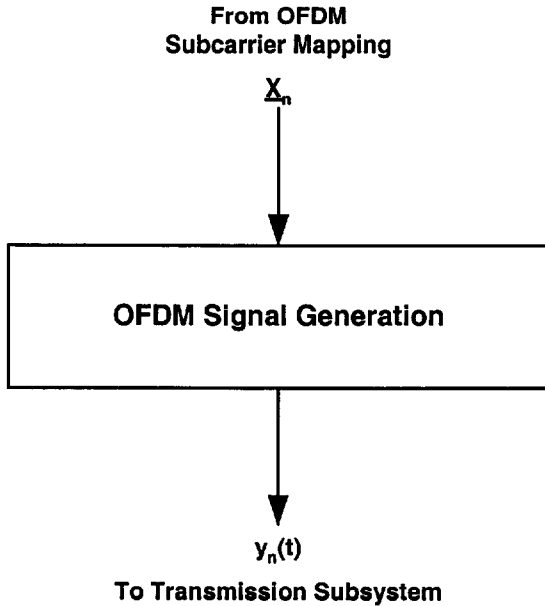


Figure 4-1 OFDM Signal Generation Conceptual Block Diagram

The input to OFDM Signal Generation is a complex vector \underline{X}_n of length L , representing the complex constellation values for each OFDM subcarrier in OFDM symbol n . The output of OFDM Signal Generation is a complex, baseband, time-domain pulse $y_n(t)$, representing the digital portion of the FM IBOC signal for OFDM symbol n .

4.2 Functionality

Let $\underline{X}_n[k]$ be the scaled constellation points from OFDM Subcarrier Mapping for the n^{th} symbol, where $k = 0, 1, \dots, L-1$ indexes the OFDM subcarriers. Let $y_n(t)$ denote the time-domain output of OFDM Signal Generation for the n^{th} symbol. Then $y_n(t)$ is written in terms of $\underline{X}_n[k]$ as follows,

$$y_n(t) = h(t - nT_s) \cdot \sum_{k=0}^{L-1} \underline{X}_n[k] \cdot e^{j2\pi\Delta f \left[k - \frac{(L-1)}{2} \right] \cdot (t - nT_s)}$$

where $n = 0, 1, \dots, \infty$, $0 \leq t < \infty$, $L = 1093$ is the total number of OFDM subcarriers, and T_s and Δf are the OFDM symbol duration and OFDM subcarrier spacing, respectively, as defined in Subsection 2.5.

The *pulse-shaping function* $h(\xi)$ is defined as:

$$h(\xi) = \begin{cases} \cos\left(\pi \frac{\alpha T - \xi}{2\alpha T}\right) & \text{if } 0 < \xi < \alpha T \\ 1 & \text{if } \alpha T \leq \xi \leq T \\ \cos\left(\pi \frac{T - \xi}{2\alpha T}\right) & \text{if } T < \xi < T(1 + \alpha) \\ 0 & \text{elsewhere} \end{cases}$$

where α is the cyclic prefix width defined in Subsection 2.5, and $T = \frac{1}{\Delta f}$ is the reciprocal of the OFDM subcarrier spacing.

4.3 Transmission Subsystem

4.3.1 Introduction

The Transmission Subsystem formats the baseband FM IBOC waveform for transmission through the VHF channel. Functions include symbol concatenation and frequency up-conversion. In addition, when transmitting the Hybrid or Extended Hybrid waveforms, this function delays and modulates the baseband analog signal before combining it with the digital waveform.

The input to this module is a complex, baseband, time-domain OFDM symbol, $y_n(t)$, from the OFDM Signal Generation function. A baseband analog signal $m(t)$ is also input from an analog source, along with optional subsidiary communications authorization (SCA) signals, when transmitting the Hybrid or Extended Hybrid waveform. In addition, analog diversity delay control (DD) is input from Layer 2 via the CCH. The output of this module is the VHF FM IBOC

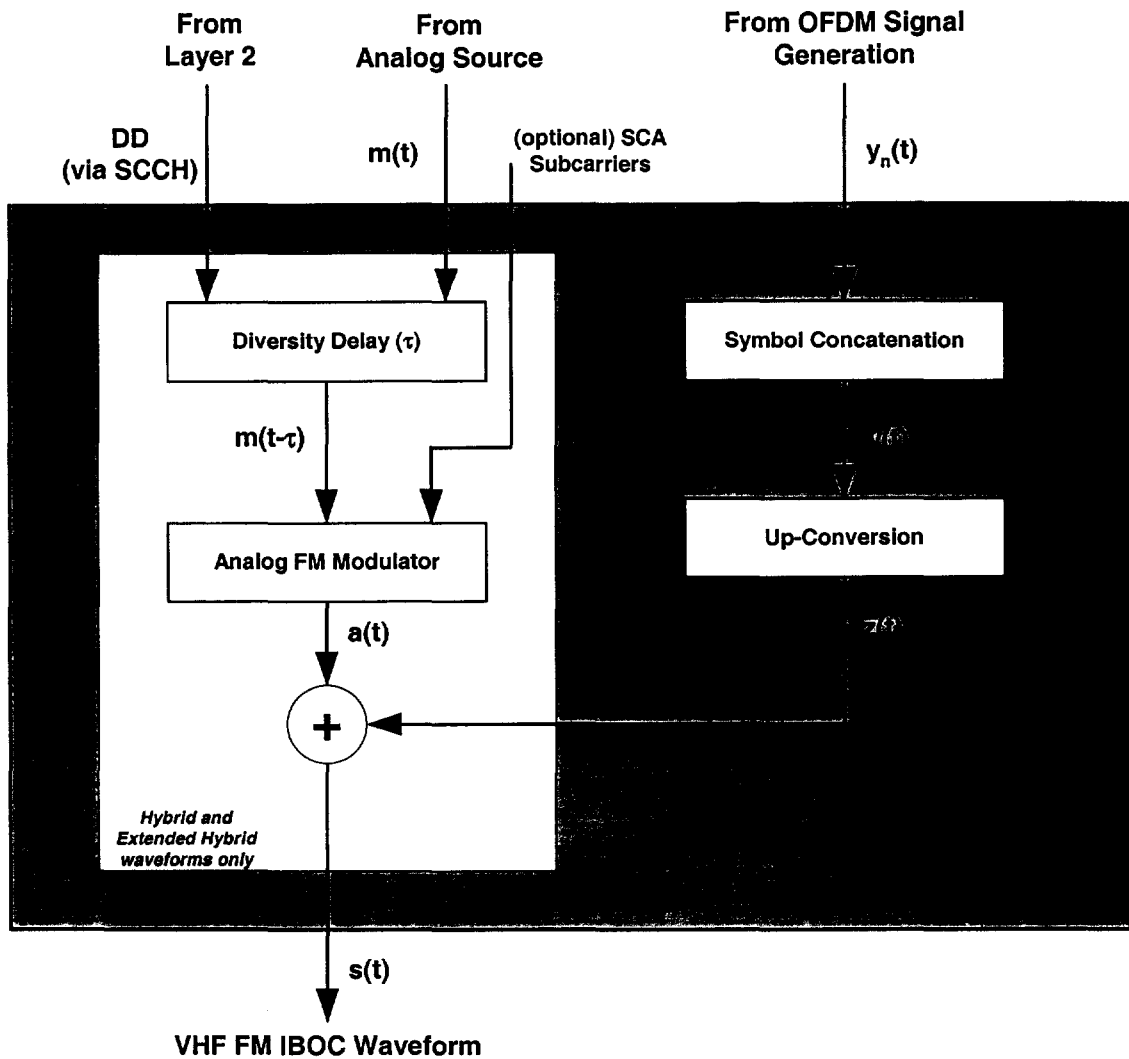


Figure 4-2 Hybrid/Extended Hybrid Transmission Subsystem Functional Block Diagram

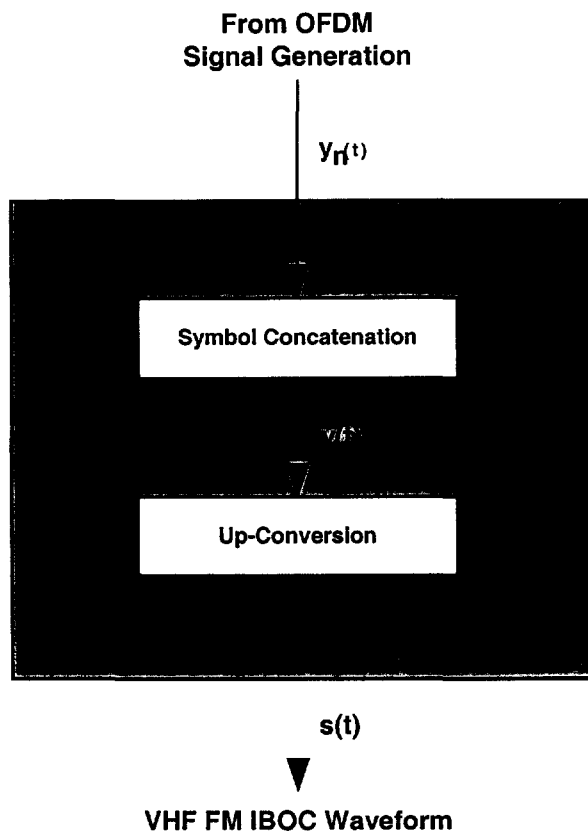


Figure 4-3 All Digital Transmission Subsystem Functional Block Diagram

4.4 Functional Components

The functional components of the Transmission Subsystem are specified in Subsection 4.4.1 through Subsection 4.4.5.

4.4.1 Symbol Concatenation

The individual time-domain OFDM symbols generated by OFDM Signal Generation are concatenated to produce a continuum of pulses over $t = 0, \dots, \infty$, as follows:

$$y(t) = \sum_{n=0}^{\infty} y_n(t)$$

4.4.2 Up-Conversion

The concatenated digital signal $y(t)$ is translated from baseband to the RF carrier frequency as follows:

$$z(t) = \text{Re} \left(e^{j2\pi f_c t} \cdot y(t) \right)$$

where f_c is the VHF allocated channel frequency and $\text{Re}[\]$ denotes the real component of the complex quantity. For the All Digital waveform, the output of the up-converter is the transmitted VHF FM IBOC waveform, and therefore, $s(t) = z(t)$.

The carrier frequency spacing and channel numbering scheme are compatible with Title 47 CFR §73.201. The carriers retain their 200-kHz spacing over the 88.0- to 108.0-MHz frequency range. Channels are numbered from 201 to 300, where channel 201 is centered on 88.1 MHz and channel 300 is centered on 107.9 MHz. The absolute accuracy of the carrier frequency is defined in Appendix A.

4.4.3 Diversity Delay

When broadcasting the Hybrid and Extended Hybrid waveforms, $z(t)$ is combined with the analog FM signal $a(t)$, as shown in Figure 4-2. The first step in generating $a(t)$ is the application of diversity delay to the baseband analog signal $m(t)$.

The analog diversity delay control bit (DD), received from Layer 2 via the SCCH, is used by upper protocol layers to enable or disable the diversity delay. If DD is 0, the diversity delay is disabled; if DD is 1, it is enabled. When diversity delay is enabled, an adjustable delay τ is applied to the baseband analog signal $m(t)$. The delay is set so that, at the output of the analog/digital combiner, $a(t)$ lags the corresponding digital signal $z(t)$ by T_{dd} . In the IBOC system the analog and digital signals carry the same audio program with the analog audio delayed from the corresponding digital audio by T_{dd} at the output of the analog/digital combiner. The delay is adjustable to account for processing delays in the analog and digital chains.

The absolute accuracy of the diversity delay, when enabled, is defined in Appendix A.

4.4.4 Analog FM Modulator

For the Hybrid and Extended Hybrid waveforms, the appropriately delayed baseband analog signal $m(t-\tau)$ is frequency modulated to produce an RF analog FM waveform identical to existing analog signals. The FM-modulated analog signal, including any SCAs, will maintain compatibility with Title 47 CFR Part 73, Subparts B, C, and H. In addition, the analog signal will be compatible with the emergency alert system (EAS) as specified in Title 47 CFR Part 11.

4.4.5 Analog/Digital Combiner

When broadcasting the Hybrid or Extended Hybrid waveform, the analog-modulated FM RF signal is combined with the digitally-modulated RF signal to produce the VHF FM IBOC waveform, $s(t)$. Both the analog and digital portions of the waveform are centered on the same carrier frequency.

The levels of each digital sideband in the output spectrum are appropriately scaled by OFDM Subcarrier Mapping. The subcarrier scale factors and power ratios with respect to the total power of the analog FM carrier are provided in Appendix A.

The spectral noise and emission limits of the IBOC digital signal are defined in Appendix A.

4.4.6 Use of On Channel Repeaters

The use of OFDM modulation in the FM IBOC system allows on-channel digital repeaters to fill areas of desired coverage where signal losses due to terrain and/or shadowing are severe. A typical application

would be where mountains or other terrain obstructions within the station's service areas limit analog or digital performance.

iBiquity's FM IBOC system operates with an effective guard time between OFDM symbols of approximately 150 microseconds¹. To avoid significant intersymbol interference the effective coverage in the direction of the primary transmission system should be limited to within 14 miles. Specifically the ratio of the signal from the primary transmitter to the booster signal should be at least 10 dB at locations more than 14 miles from the repeater in the direction of the primary antenna. Performance and distances between on-channel boosters can be improved through the use of directional antennas to protect the main station. The coverage in the direction pointing away from the primary antenna can be arbitrarily large, but must conform to the FCC coverage allocation for that station.

4.4.7 GPS Synchronization

In order to ensure precise time synchronization, for rapid station acquisition and booster synchronization, each station is GPS locked.

This is normally accomplished through synchronization with a signal synchronized in time and frequency to the Global Positioning System (GPS)². Transmissions that are not locked to GPS, will not benefit from fast tuning since they cannot be synchronized with other stations³.

¹ 150 microseconds equates to a 28 mile propagation distance.

² GPS Locked stations are referred to as Level I: GPS-locked transmission facilities

³ Level II: Non-GPS locked transmission facilities

5 Waveforms and Spectra

5.1 Introduction

This section describes the output spectrum for each of the three digital waveform types: Hybrid, Extended Hybrid, and All Digital. Each spectrum is divided into several sidebands, which represent various subcarrier groupings. All spectra are represented at baseband.

5.2 Frequency Partitions and Spectral Conventions

The OFDM subcarriers are assembled into *frequency partitions*. Each frequency partition is comprised of eighteen data subcarriers and one reference subcarrier, as shown in Figure 5-1 (ordering A) and Figure 5-2 (ordering B). The position of the reference subcarrier (ordering A or B) varies with the location of the frequency partition within the spectrum.

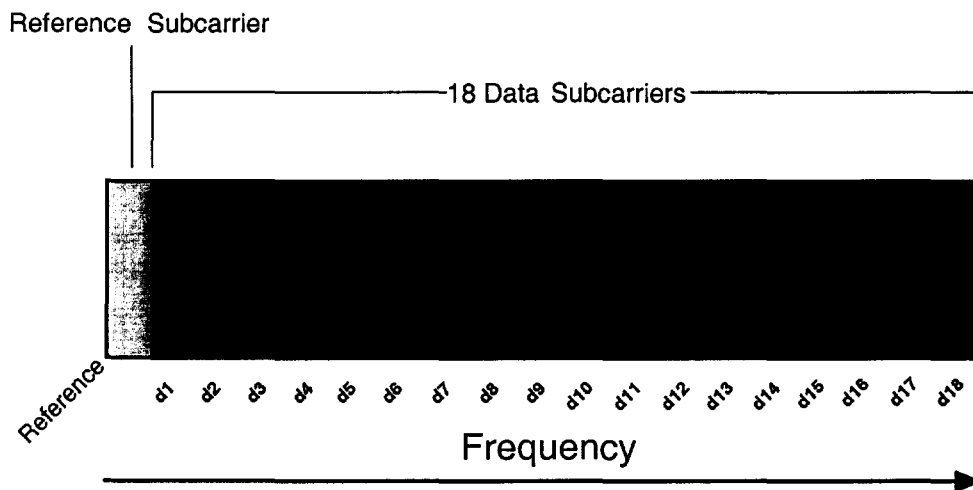


Figure 5-1 Frequency Partition—Ordering A

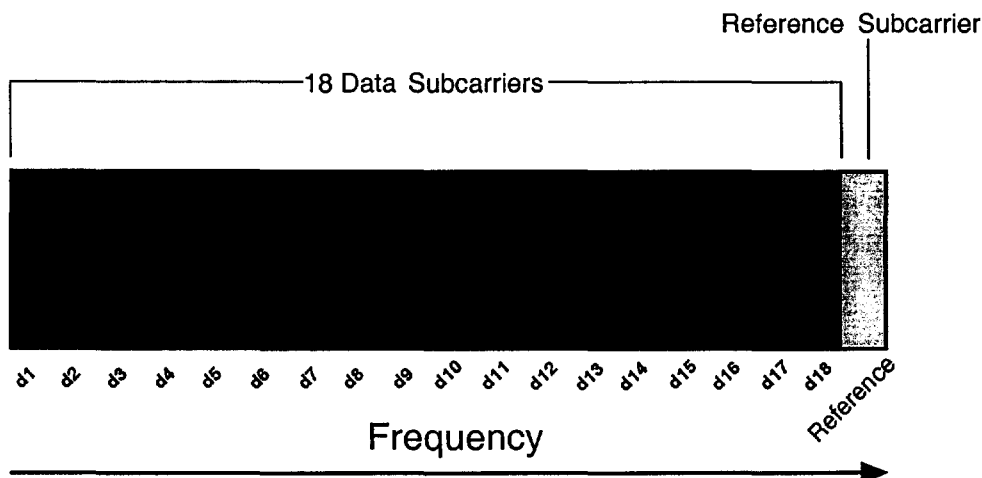


Figure 5-2 Frequency Partition—Ordering B

For each frequency partition, data subcarriers d1 through d18 convey the L2 SDUs, while the reference subcarriers convey system control. Subcarriers are numbered from 0 at the center frequency to ± 546 at either end of the channel frequency allocation.

Besides the reference subcarriers resident within each frequency partition, depending on the service mode, up to five additional reference subcarriers are inserted into the spectrum at subcarrier numbers -546 , -279 , 0 , 279 , and 546 . The overall effect is a regular distribution of reference subcarriers throughout the spectrum. For notational convenience, each reference subcarrier is assigned a unique identification number between 0 and 60. All *lower sideband* reference subcarriers are shown in Figure 5-3. All *upper sideband* reference subcarriers are shown in Figure 5-4. The figures indicate the relationship between reference subcarrier numbers and OFDM subcarrier numbers.

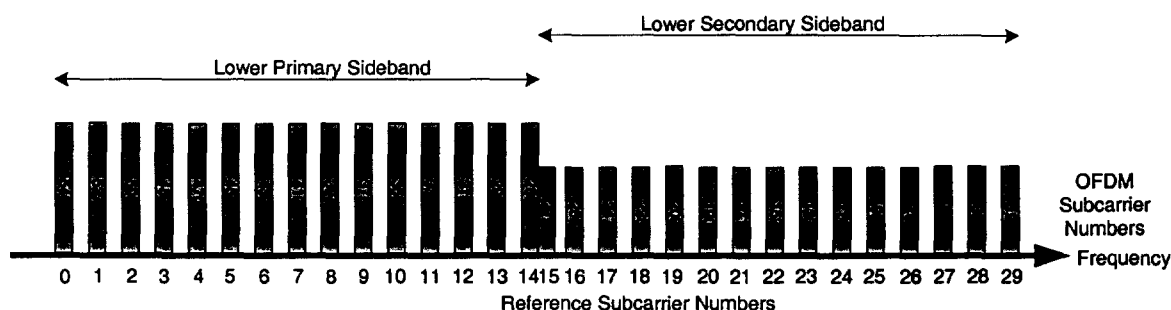


Figure 5-3 Lower Sideband Reference Subcarrier Spectral Mapping

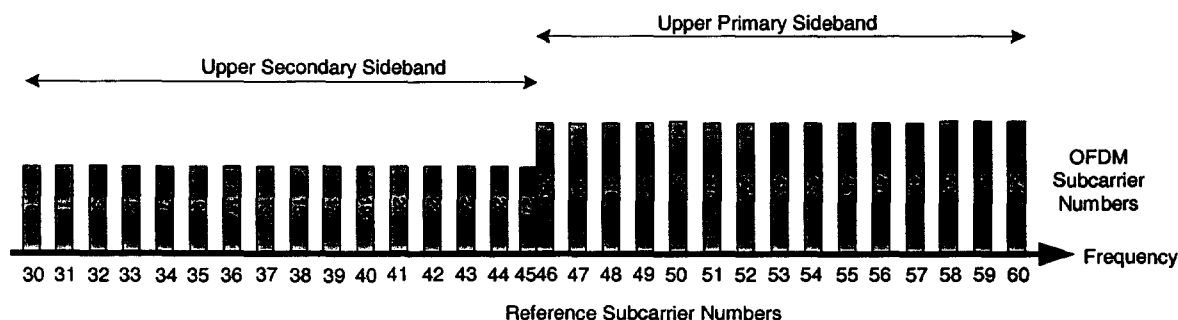


Figure 5-4 Upper Sideband Reference Subcarrier Spectral Mapping

Each spectrum described in the remaining subsections shows the subcarrier number and center frequency of certain key OFDM subcarriers. The center frequency of a subcarrier is calculated by multiplying the subcarrier number by the OFDM subcarrier spacing Δf . The center of subcarrier 0 is located at 0 Hz. In this context, center frequency is relative to the radio frequency (RF) *allocated channel*.

For example, the upper Primary Main sideband is bounded by subcarriers 356 and 546, whose center frequencies are located at 129,361 Hz and 198,402 Hz, respectively. The frequency span of the Primary Main sideband is 69,041 Hz. (198,402 – 129,361).

5.3 Hybrid Spectrum

The digital signal is transmitted in PM sidebands on either side of the analog FM signal, as shown in Figure 5-5. Each PM sideband is comprised of ten frequency partitions, which are allocated among subcarriers 356 through 545, or -356 through -545. Subcarriers 546 and -546, also included in the PM sidebands, are additional reference subcarriers. The amplitude of the subcarrier within Primary Main sidebands are uniformly scaled by an *amplitude scale factor*, a_0 . The amplitude scaling factor is described in Appendix A. Table 5-1 summarizes the upper and lower Primary Main sidebands for the Hybrid waveform.

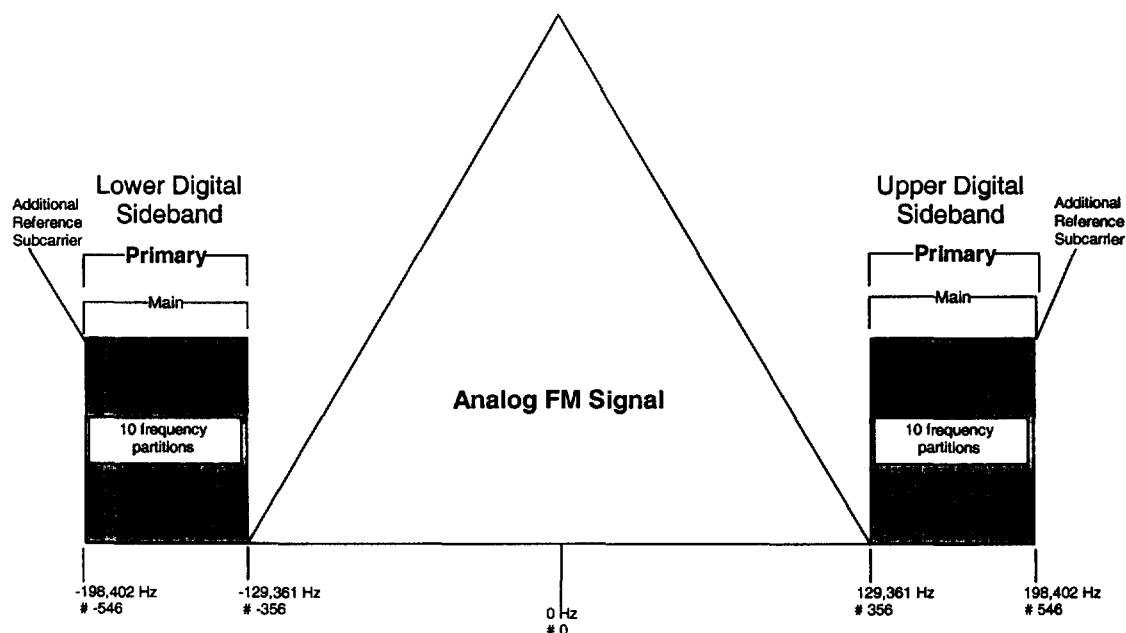


Figure 5-5 Spectrum of the Hybrid Waveform—Service Mode MP1

Table 5-1 Hybrid Waveform Spectral Summary—Service Mode MP1

Sideband	Number of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Ampl. Scale Factor	Frequency Span (Hz)	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	a_0	69,041	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	a_0	69,041	Includes additional reference subcarrier - 546

Note: Refer to Appendix A for details regarding the amplitude scale factors shown above.

5.4 Extended Hybrid Spectrum

The Extended Hybrid waveform is created by adding Primary Extended sidebands to the Primary Main sidebands present in the Hybrid waveform, as shown in Figure 5-6. Depending on the service mode, one, two, or four frequency partitions can be added to the inner edge of each Primary Main sideband.

Each Primary Main sideband consists of ten frequency partitions and an additional reference subcarrier spanning subcarriers 356 through 546, or -356 through -546. The upper Primary Extended sidebands include subcarriers 337 through 355 (one frequency partition), 318 through 355 (two frequency partitions), or 280 through 355 (four frequency partitions). The lower Primary Extended sidebands include subcarriers -337 through -355 (one frequency partition), -318 through -355 (two frequency partitions), or -280 through -355 (four frequency partitions). The subcarriers within Primary Extended sidebands are uniformly scaled the same *amplitude scale factor*, a_0 , as the Primary Main sidebands. The amplitude scaling factor is described in Appendix A. Table 5-2 summarizes the Upper and Lower Primary sidebands for the Extended Hybrid waveform.

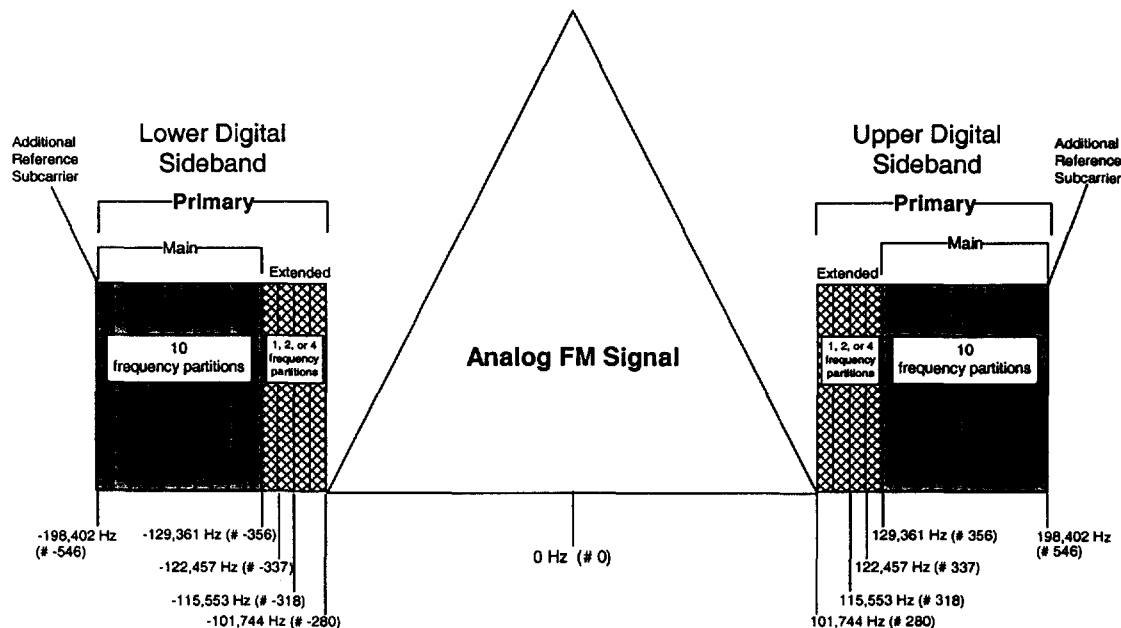


Figure 5-6 Spectrum of the Extended Hybrid Waveform—Service Modes MP2 through MP4

Table 5-2 Extended Hybrid Waveform Spectral Summary--Service Modes MP2 through MP4

Sideband	Number of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequency (Hz from channel center)	Ampl. Scale Factor	Frequency Span (Hz)	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	a_0	69,041	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	a_0	69,041	Includes additional reference subcarrier -546
Upper Primary Extended (1 frequency partition)	1	A	337 to 355	122,457 to 128,997	a_0	6,540	none
Lower Primary Extended (1 frequency partition)	1	B	-337 to -355	-122,457 to -128,997	a_0	6,540	none
Upper Primary Extended (2 frequency partitions)	2	A	318 to 355	115,553 to 128,997	a_0	13,444	none
Lower Primary Extended (2 frequency partitions)	2	B	-318 to -355	-115,553 to -128,997	a_0	13,444	none
Upper Primary Extended (4 frequency partitions)	4	A	280 to 355	101,744 to 128,997	a_0	27,253	none
Lower Primary Extended (4 frequency partitions)	4	B	-280 to -355	-101,744 to -128,997	a_0	27,253	none

Note: Refer to Appendix A for details regarding the amplitude scale.

5.5 All Digital Spectrum

The All Digital waveform is constructed by removing the analog signal, fully expanding the bandwidth of the primary digital sidebands, and adding lower-power secondary sidebands in the spectrum vacated by the analog signal. The spectrum of the All Digital waveform is shown in Figure 5-7.

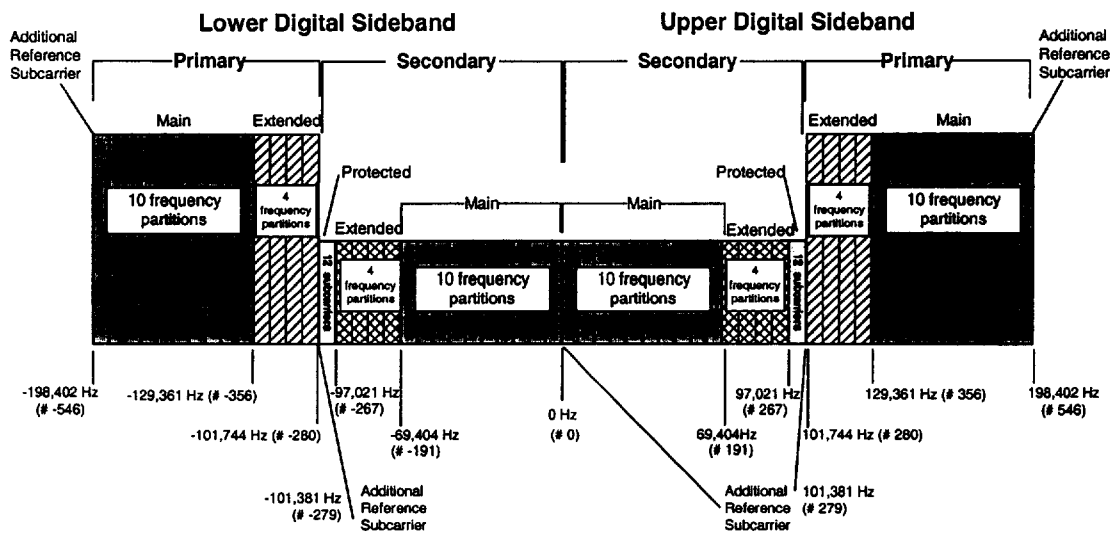


Figure 5-7 Spectrum of the All Digital Waveform—Service Modes MP5 through MP7, MS1 through MS4

In addition to the ten main frequency partitions, all four extended frequency partitions are present in each primary sideband of the All Digital waveform. Each secondary sideband also has ten Secondary Main (SM) and four Secondary Extended frequency partitions. Unlike the primary sidebands, however, the Secondary Main frequency partitions are mapped nearer to channel center with the extended frequency partitions farther from the center.

Each secondary sideband also supports a small Secondary Protected (SP) region consisting of 12 OFDM subcarriers and reference subcarriers 279 and -279. The sidebands are referred to as “protected” because they are located in the area of spectrum *least* likely to be affected by analog or digital interference. An additional reference subcarrier is placed at the center of the channel (0). Frequency partition ordering of the SP region does not apply since the SP region does not contain frequency partitions as defined in Figure 5-1 and Figure 5-2.

Each Secondary Main sideband spans subcarriers 1 through 190 or -1 through -190. The upper Secondary Extended sideband includes subcarriers 191 through 266, and the upper Secondary Protected sideband includes subcarriers 267 through 278, plus additional reference subcarrier 279. The lower Secondary Extended sideband includes subcarriers -191 through -266, and the lower Secondary Protected sideband includes subcarriers -267 through -278, plus additional reference subcarrier -279. The total frequency span of the entire All Digital spectrum is 396,803 Hz. The subcarriers within the Primary Main and Primary Extended sidebands are scaled by an amplitude scale factor, a_2 , as indicated in Table 5-3. The subcarriers within the Secondary Main, Secondary Extended and Secondary Protected sidebands are uniformly scaled by an amplitude scale factor having four discrete levels a_4 – a_7 , as indicated in Table 5-3. Table 5-3 summarizes the upper and lower, primary and secondary sidebands for the All Digital waveform.

Table 5-3 All Digital Waveform Spectral Summary—Service Modes MP5 through MP7, MS1 through MS4

Sideband	Number of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequency (Hz from channel center)	Ampl. Scale Factor	Frequency Span (Hz)	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	a_2	69,041	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	a_2	69,041	Includes additional reference subcarrier - 546
Upper Primary Extended	4	A	280 to 355	101,744 to 128,997	a_2	27,253	none
Lower Primary Extended	4	B	-280 to -355	-101,744 to -128,997	a_2	27,253	none
Upper Secondary Main	10	B	0 to 190	0 to 69,041	a_2	69,041	Includes additional reference subcarrier 0
Lower Secondary Main	10	A	-1 to -190	-363 to -69,041	a_2	68,678	none
Upper Secondary Extended	4	B	191 to 266	69,404 to 96,657	$a_4 - a_7$	27,253	none
Lower Secondary Extended	4	A	-191 to -266	-69,404 to -96,657	$a_4 - a_7$	27,253	none
Upper Secondary Protected	N/A	N/A	267 to 279	97,021 to 101,381	$a_4 - a_7$	4,360	Includes additional reference subcarrier 279
Lower Secondary Protected	N/A	N/A	-267 to -279	-97,021 to -101,381	$a_4 - a_7$	4,360	Includes additional reference subcarrier 279

Note: Refer to Appendix A for details regarding the amplitude scale factors.

Supplement A FM Transmission Specifications

A.1 Introduction

This appendix presents the key transmission specifications for the FM IBOC system, as described in the body of this document.

A.2 Synchronization Tolerances

The synchronization tolerances are specified in Subsection A.2.1 through Subsection A.2.3. The system shall support two levels of synchronization for each broadcaster:

- Level I: GPS-locked transmission facilities
- Level II: Non-GPS-locked transmission facilities

Normally, transmission facilities will operate as Level I facilities in order to support numerous advanced system features.

A.2.1 Analog Diversity Delay

The absolute accuracy of the analog diversity delay in the transmission signal will be within ± 10 microseconds (μsec) for both synchronization Level I and Level II transmission facilities.

Diversity delay accuracy will be verified with a calibrated test receiver receiving the RF channel under test. A digitally generated 4 kHz sinusoidal test tone at a level of -6 dB from full scale will be applied to both the analog and digital transmit signal paths. The tone will be a pulsed signal, consisting of a repeating pattern of 0.5 seconds on followed by 4.5 seconds off.

A.2.2 RF Carrier Frequency and OFDM Symbol Clock

For synchronization Level I transmission facilities, the absolute accuracy of the carrier frequency and OFDM symbol clock frequency will be maintained to within 1 part per 10^8 at all times.

For synchronization Level II transmission facilities, the absolute accuracy of the carrier frequency and OFDM symbol clock frequency will be maintained to within 2 parts per 10^6 at all times.

A.2.3 GPS Phase Lock

For Level I transmission facilities, all transmissions will maintain phase lock to absolute GPS time within $\pm 1 \mu\text{sec}$.

If the above specification in a synchronization Level I transmission facility is violated, due to a GPS outage or other occurrence, it will be classified as a synchronization Level II transmission facility until the above specification is again met.

A.3 IBOC Noise and Emissions Limits

The noise and emissions limits are as specified in Subsection A.3.1 through Subsection A.3.3.

A.3.1 Analog Waveform

Analog transmissions will remain within the Federal Communications Commission (FCC) emissions mask in accordance with CFR Title 47 §73.317 and summarized in Table A-1. Measurements of the analog signal are made at the antenna input by averaging the power spectral density in a 1-kHz bandwidth over a 10-second segment of time.

Table A-1 FCC RF Spectral Emissions Mask

Offset from Carrier Frequency (kHz)	Power Spectral Density Relative to Unmodulated Analog FM Carrier (dBc/kHz)
120 to 240	-25
240 to 600	-35
greater than 600	-80, or $-43 - (10 \cdot \log_{10} [\text{power in watts}])$, whichever is less, where [power in watts] refers to the total unmodulated transmitter output carrier power

A.3.2 Hybrid and Extended Hybrid Waveforms

Hybrid and Extended Hybrid waveform transmissions including noise and spuriously generated signals from all sources, including phase noise of the IBOC exciter and intermodulation products will remain within the Noise and Emissions Limit as depicted in Figure A-1 and summarized in Table A-1. Measurements of the digitally-modulated signals are relative to the PM sidebands of the digital carriers spectral density in a 1 kHz bandwidth.

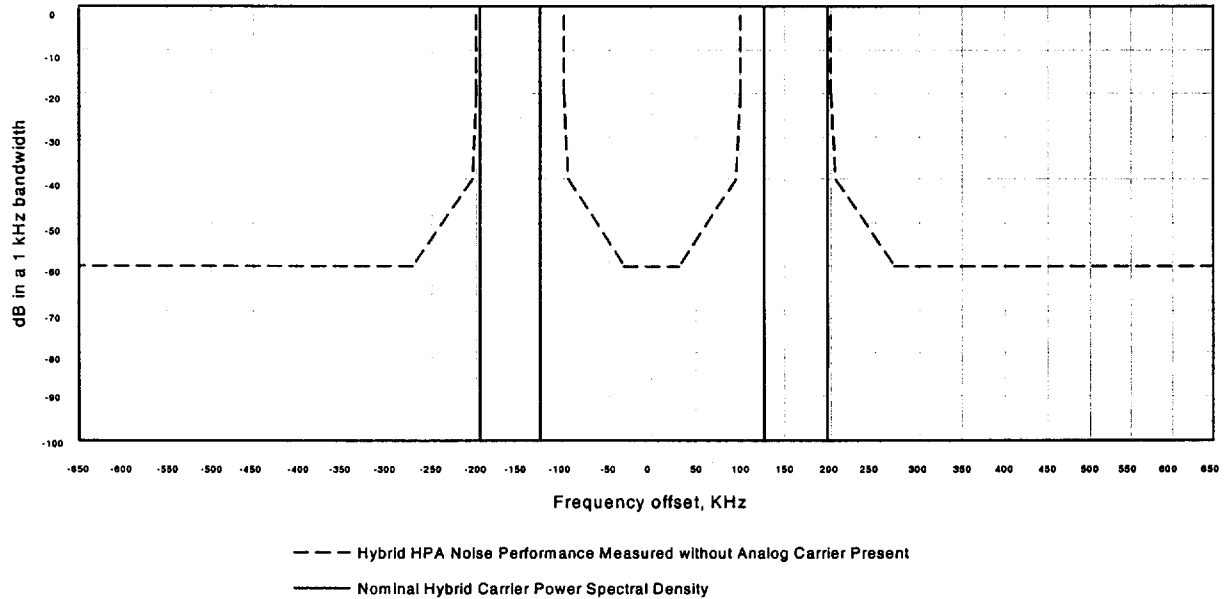


Figure A-1 IBOC FM HPA Hybrid Mode Signal and Noise Emission Limits

Table A-1 IBOC FM HPA Hybrid Mode Signal and Noise Emission Limits

Frequency, F, Offset Relative to Carrier	Level, dB/kHz
0-30 kHz offset	-60 dB
30-95 kHz offset	$[-60 + (frequency \text{ in kHz} -30 \text{ kHz}) * 0.3077] \text{ dB}$
95-100 kHz offset	$[-20 + (frequency \text{ in kHz} -100 \text{ kHz}) * 4.0] \text{ dB}$
200-205 kHz offset	$[-20 - (frequency \text{ in kHz} -200 \text{ kHz}) * 4.0] \text{ dB}$
205-270 kHz offset	$[-40 - (frequency \text{ in kHz} -205 \text{ kHz}) * 0.3077] \text{ dB}$
>270 kHz offset	-60 dB

A.3.3 All Digital Waveform

All Digital waveform transmissions will remain within the Noise and Emissions Limit as depicted in Figure A-2 and summarized in Table A-2. Measurements of the digitally-modulated signals are relative to the PM sidebands of the digital carriers spectral density in a 1 kHz bandwidth.

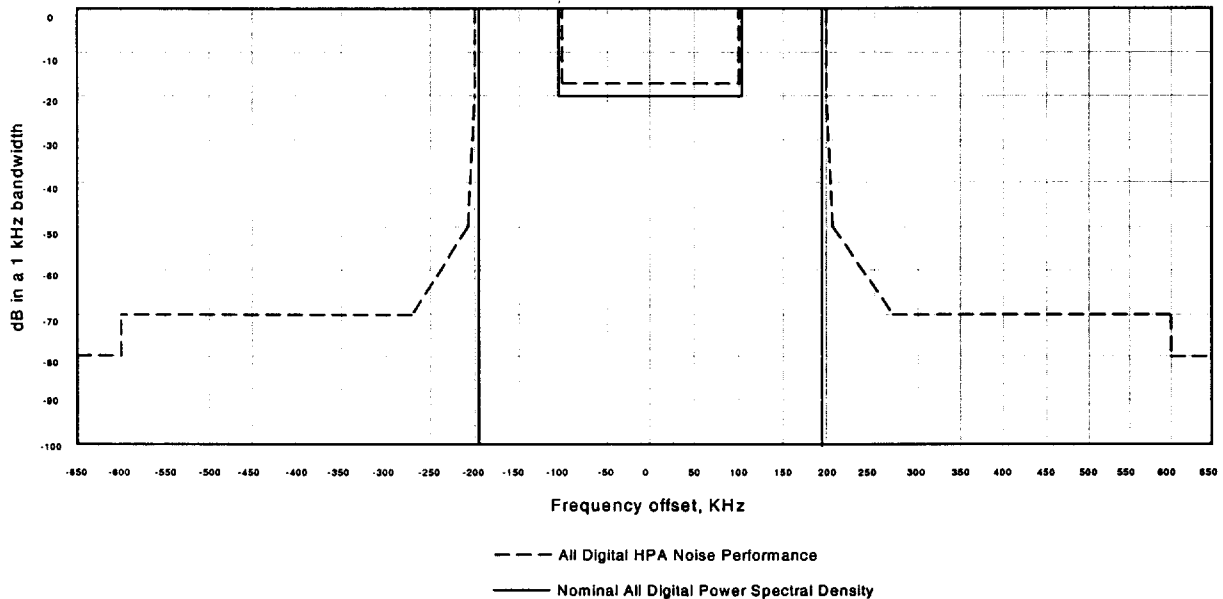


Figure A-2 IBOC FM HPA All-Digital Mode Signal and Noise Emission Limits

Table A-2 IBOC FM HPA All Digital Mode Signal and Noise Emission Limits

Frequency, F, Offset Relative to Carrier	Level, dB/kHz
0-100 kHz offset	-17dB
200-207.5 kHz offset	$[-20 - (frequency \text{ in kHz} -200 \text{ kHz}) * 4.0] \text{ dB}$
207.5-270 kHz offset	$[-50 - (frequency \text{ in kHz} -207.5 \text{ kHz}) * 0.3200] \text{ dB}$
270-600 kHz offset	-70 dB
>600 kHz offset	-80 dB

A.4 Digital Sideband Levels

The amplitude scaling of each OFDM subcarrier within each digital sideband is given in Table A-3 for the Hybrid, Extended Hybrid, and All Digital waveforms. The values for the Hybrid waveforms are specified relative to the total power of the unmodulated analog FM carrier (assumed equal to 1). The values for the All Digital waveform are specified relative to the total power of the unmodulated analog FM carrier (assumed equal to 1) that would have been transmitted in the Hybrid and Extended Hybrid modes.

For the Hybrid and Extended Hybrid waveforms, the values were chosen so that the total average power in a primary digital sideband (upper or lower) is 23 dB below the total power of unmodulated analog FM carrier.

For the All Digital waveform, the values were chosen so that the total average power in a primary digital sideband (upper or lower) is at least 10 dB above the total power in the Hybrid primary digital sidebands. In addition, the values were chosen so that the total average power in the secondary digital sidebands (upper and lower) is at least 20 dB below the total power in the All Digital primary digital sidebands.

Table A-3 OFDM Subcarrier Scaling

Waveform	Mode	Sidebands	Amplitude Scale Factor Notation	Amplitude Scale Factor (relative to total analog FM power)	Scale Factor (dB, relative to total analog FM power)
Hybrid	MP1	Primary	a_0	5.123×10^{-3}	-41.39
Extended Hybrid	MP2 – MP7	Primary	a_0	5.123×10^{-3}	-41.39
All Digital	MP-5 – MP7	Primary	a_2	1.67×10^{-2}	-31.39
		Secondary	a_4	5.123×10^{-3}	-41.39
	MS1 – MS4	Secondary	a_5	3.627×10^{-3}	-44.39
		Secondary	a_6	2.567×10^{-3}	-47.39
		Secondary	a_7	1.181×10^{-3}	-50.39

⁴ Amplitude Scale Factor per IBOC subcarrier

⁵ Amplitude Scale factor in dB measured in 1 kHz bandwidth

Glossary

For the purpose of better understanding this document, the following definitions apply:

All Digital waveform - The transmitted waveform composed entirely of digitally modulated subcarriers (subcarrier -546 to +546) without an analog FM signal. Use of this waveform will normally follow an initial transitional phase utilizing hybrid waveforms incorporating both analog and digital modulation (see *Hybrid waveform* and *Extended Hybrid waveform*).

allocated channel – One of the one hundred possible frequency assignments in the FM band, as defined in Reference [10].

amplitude modulation (AM) - Modulation in which the amplitude of a carrier wave is varied in accordance with the amplitude of the modulating signal.

amplitude scale factor – A factor which multiplies the baseband components of a particular sideband of the transmitted spectrum to constrain the radiated power to a prescribed level.

analog signal - refers to signals that are modulated on the main carrier by conventional high-modulation-index frequency modulation. (see *digital signal*).

Binary Phase Shift Keying (BPSK) – A form of digital phase modulation that assigns one of two discrete phases, differing by 180 degrees, to the carrier. Each BPSK symbol conveys one bit of information.

channel encoding - The process used to add redundancy to each of the logical channels to improve the reliability of the transmitted information.

characterization parameters - The unique set of defining parameters for each logical channel for a given service mode. The channel encoding, interleaving, spectral mapping, and diversity delay of the logical channel determine its characterization parameters.

code rate - Defines the increase in overhead on a coded channel resulting from channel encoding. It is the ratio of information bits to the total number of bits after coding.

convolutional encoding - A form of forward error-correction channel encoding that inserts coding bits into a continuous stream of information bits to form a predictable structure. Unlike a block encoder, a convolutional encoder has memory; its output is a function of current and previous inputs.

differential encoding - Encoding process in which signal states are represented as changes to succeeding values rather than absolute values.

digital signal - refers to signals that are digitally modulated on subcarriers by OFDM (q.v.) (see *analog signal*).

diversity delay - Imposition of a fixed time delay in one of two channels carrying the same information to defeat non-stationary channel impairments such as fading and impulsive noise.

Extended Hybrid waveform - The transmitted waveform composed of the analog FM signal plus digitally modulated primary main subcarriers (subcarriers +356 to +546 and -356 to -546) and some or all primary extended subcarriers (subcarriers +280 to +355 and -280 to -355). This waveform will normally be used during an initial transitional phase preceding conversion to the All Digital waveform (see *All Digital waveform* and *Hybrid waveform*).

fading - The variation (with time) of the amplitude or relative phase (or both) of one or more frequency components of a received signal.

frequency modulation (FM) - Modulation in which the instantaneous frequency of a sine wave carrier is caused to depart from the center frequency by an amount proportional to the instantaneous amplitude of the modulating signal.

frequency partition - A group of 19 OFDM subcarriers containing 18 data subcarriers and one reference subcarrier.

Hybrid waveform - The transmitted waveform composed of the analog FM-modulated signal, plus digitally modulated Primary Main subcarriers (subcarriers +356 to +546 and -356 to -546). This waveform will normally be used during an initial transitional phase preceding conversion to the All Digital waveform (see *All Digital waveform* and *Extended Hybrid waveform*).

interleaving - A reordering of the message bits to distribute them in time (over different OFDM symbols) and frequency (over different OFDM subcarriers) to mitigate the effects of signal fading and interference.

interleaving process - A series of manipulations performed on one or more coded transfer frames (vectors) to reorder their bits into one or more interleaver matrices whose contents are destined for a particular portion of the transmitted spectrum.

L1 block - A unit of time of duration T_b . Each L1 frame is comprised of 16 L1 blocks.

L1 block count - An index that indicates one of 16 equal subdivisions of an L1 frame.

L1 block pair - Two contiguous L1 blocks. A unit of time duration T_p .

L1 block pair rate - The rate, equal to the reciprocal of the L1 block pair duration, $\left(\frac{1}{T_p}\right)$, at which selected transfer frames are conducted through Layer 1.

L1 block rate - The rate, equal to the reciprocal of the L1 block duration, $\left(\frac{1}{T_b}\right)$, at which selected transfer frames are conducted through Layer 1.

L1 frame - A specific time slot of duration T_f identified by an ALFN. The transmitted signal may be considered to consist of a series of L1 frames.

L1 frame rate - The rate, equal to the reciprocal of the L1 frame duration $\left(\frac{1}{T_f}\right)$, at which selected transfer frames are conducted through Layer 1.

latency - The time delay that a logical channel imposes on a transfer frame as it traverses Layer 1. One of the three characterization parameters. (see *robustness* and *transfer*).

Layer 1 (L1) - The lowest protocol layer in the OSI Reference Model (also known as the Physical layer). Primarily concerned with physical connections and the transmission of data over a communication channel.

Layer 2 (L2) - The Data Link layer in the OSI Reference Model. Primarily concerned with specific requirements for frames (such as blocks and packets), synchronization, and error control.

logical channel - A signal path that conducts transfer frames from Layer 2 through Layer 1 with a specified grade of service.

lower sideband - The group of OFDM subcarriers (subcarriers number -1 through -546) below the carrier frequency.

OFDM Signal Generation - The function that generates the modulated baseband signal in the time domain.

OFDM subcarrier - One of 1093 possible narrowband PSK-modulated carriers within the allocated channel, which, taken in aggregate, constitute the frequency domain representation of one OFDM symbol.

OFDM subcarrier mapping – The function that assigns the interleaved logical channels (interleaver partitions) to the OFDM subcarriers (frequency partitions).

OFDM symbol - Time domain pulse of duration T_s , representing all the active subcarriers and containing all the data in one row from the interleaver and system control data sequence matrices. The transmitted waveform is the concatenation of successive OFDM symbols.

Open Systems Interconnection (OSI) Layered Model - A multi-tiered model of network architecture and a suite of protocols (a protocol stack) to implement it. Developed by the International Standards Organization (ISO) in 1978 as a framework for international standards in heterogeneous computer network architecture (see Reference [8]). The OSI architecture is logically divided into seven protocol layers, from lowest to highest, as follows:

- Layer 1 - Physical layer
- Layer 2 - Data Link layer
- Layer 3 - Network layer
- Layer 4 - Transport layer
- Layer 5 - Session layer
- Layer 6 - Presentation layer
- Layer 7 - Application layer

Each layer uses the layer immediately below it and provides a service to the layer above.

Orthogonal Frequency Division Multiplexing (OFDM) - A parallel multiplexing scheme that modulates a data stream onto a large number of orthogonal subcarriers that are transmitted simultaneously (see *OFDM symbol*).

parity - In binary-coded data, a condition maintained so that in any permissible coded expression, the total number of “1”s or “0”s is always odd, or always even.

Primary Extended (PX) sidebands - The portion of the primary sideband that holds the additional frequency partitions (1, 2, or 4) inside the main partitions in the FM Extended Hybrid and All Digital waveforms. It consists, at most, of subcarriers 280 through 355 and -280 through -355.

Primary Main (PM) sidebands - The ten partitions in the primary sideband consisting of subcarriers 356 through 545 and -356 through -545.

primitive – basic definition of control and/or data comprising a service access point.

pulse-shaping function - A time-domain pulse superimposed on the OFDM symbol to improve its spectral characteristics.

Quadrature Phase Shift Keying (QPSK) - A form of digital phase modulation that assigns one of four discrete phases, differing by 90 degrees, to the carrier. Each QPSK symbol conveys two bits of information.

robustness - The ability of a logical channel to withstand channel impairments such as noise, interference, and fading. There are eleven distinct levels of robustness designed into Layer 1 of the FM air interface. One of the three characterization parameters. (see *latency* and *transfer*).

Scrambling - The process of summing the input data bits with a pseudo-random bit stream to randomize the time domain bit stream.

secondary sidebands - The sidebands to be added in the spectrum vacated by the analog signal. The secondary sidebands are divided into the Secondary Main (SM) sidebands containing ten frequency partitions, Secondary Extended (SX) sidebands containing four frequency partitions and the Secondary Protected (SP) sidebands containing two groups of twelve protected subcarriers. The secondary sidebands consist of subcarriers -279 through +279.

Service Access Point (SAP) - The interface between Layer 1 and Layer 2 at which the data from Layer 2 is formatted for delivery to Layer 1.

service control units (SCU) - Units of system control data transferred between Layer 2 and Layer 1.

service data units (SDU) - Units of user content transferred from Layer 2 to Layer 1.

service mode - A specific configuration of operating parameters specifying throughput, performance level, and selected logical channels.

spectral noise and emissions limit - A specification limiting the maximum level of out-of-band components of the transmitted signal.

spectral mapping - The association of specific logical channels with specific subcarriers or groups of subcarriers.

system control - Data from Layer 2 specifying service mode and analog diversity delay.

System Control Channel (SCCH) - A channel consisting of control information from Layer 2 and status information from Layer 1.

system control data sequence - A sequence of bits destined for each reference subcarrier representing the various system control components relayed between Layer 1 and Layer 2.

system control processing - The function that generates the system control data sequence.

system protocol stack - The protocols associated with operation of the layers of the OSI Reference Model.

transfer - A measure of the data throughput through a logical channel. One of the three characterization parameters. (see *latency* and *robustness*).

transfer frame - An ordered, one-dimensional collection of data bits of specified length originating in Layer 2, grouped for processing through a logical channel.

transfer frame modulus - The number of transfer frames in an L1 frame.

transfer frame multiplexer - A device that combines two or more transfer frames into a single vector.

transfer frame rate - The number of transfer frames per second entering the SAP and traversing Layer 1.

transfer frame size - The number of bytes in a transfer frame.

transmission subsystem - The functional component used to format and up-convert the baseband IBOC waveform for transmission through the very-high frequency (VHF) channel.

upper sideband - The group of OFDM subcarriers (subcarriers number 0 through +546) above the carrier frequency.

vector - A one-dimensional array.